Energy Policy 114 (2018) 413–421

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Is coal extension a sensible option for energy planning? A combined energy systems modelling and life cycle assessment approach

Diego García-Gusano[a,*], Diego Iribarren[a], Javier Dufour[a,b]

[a] Systems Analysis Unit, Instituto IMDEA Energía, 28935 Móstoles, Spain
[b] Chemical & Environmental Engineering Group, Rey Juan Carlos University, 28933 Móstoles, Spain

ARTICLE INFO

Keywords:
Coal
Energy transition
Retrofit
Sustainability

ABSTRACT

As in many countries, coal-fired power plants in Spain account for a significant contribution to the electricity mix. Nevertheless, renewable energy options and natural gas are paving the way for coal retirement. Alternatively, it is possible to reduce the emissions (especially SO_2 and NO_x) associated with coal combustion through technology retrofits focused on desulphurisation and denitrification in line with the EU Industrial Emissions Directive. Within a context of low coal and CO_2 prices, lifetime extension of coal-fired plants emerges as an option for power plant owners. This article prospectively evaluates the announced retrofit for 3560 MW of the Spanish coal power capacity under three alternative energy scenarios. In addition to prospective electricity production mixes, the evolution of key life-cycle sustainability indicators (climate change, human health, energy security) is assessed with time horizon 2050 using an enhanced energy systems optimisation model of power generation. When compared to the reference scenario, the results show that coal extension could favour the penetration of renewables in the long term. Notwithstanding, this would come at the expense of undesirable increases in climate change and human health impacts. Consequently, the implementation of the sustainability dimension in energy plans could avoid a "coal conundrum" situation in Spain.

1. Introduction

The Spanish electricity production mix shows a wide-ranging portfolio of technologies. This makes the prospective evaluation of the potential retrofitting of conventional coal thermal plants especially interesting, focusing on their techno-economic and environmental performance. The idea of implementing retrofits in coal plants, although exploratory, is founded on recent news. At the end of 2016, the former Spanish Ministry of Industry received the interest of some power generation companies to invest in retrofitting solutions for their facilities in order to meet the European Industrial Emissions Directive (IED) (2010/75/EU) requirements (European Parliament and European Council, 2010). Plant owners asked for extra time, thus opening a period to either retrofit or close down by 30th June 2020. Additionally, there is a national plan resulting from another EU regulation (Council Decision 2010/787/EU) forcing the closure of uncompetitive coal mines (Council of the European Union, 2010). Hence, power generation with Spanish coal will vanish. Nevertheless, Spanish coal-fired power plants could continue operating by using imported coal and adapting to the new NO_x, SO_2 and particulate matter (PM) limits. This article evaluates this uncertain situation by means of an energy systems modelling (ESM) approach based on cost optimisation of the Spanish electricity production mix from 2016 to 2050. The value-added is the consideration of a life-cycle sustainability perspective through the prospective assessment of climate change, human health and energy security.

1.1. Retrofitting coal power plants in Spain

Coal burning is one of the main stationary sources of CO_2 and local air pollution. In this sense, the European IED aims at operating changes in large combustion plants to enhance their environmental profile, with reductions in NO_x, SO_2 and PM emissions according to certain threshold values included in each Transitional National Plan (TNP). Even though retrofitting existing coal-fired power plants is not a solution in terms of climate change abatement –unless retrofits also include CO_2 capture systems–, it is highly successful regarding NO_x and SO_2 emissions, with the implementation of deNO_x and deSO_x systems, leading to reductions around 50–70% in NO_x and 90% in SO_2 (Fernández Montes, 2016).

In the specific case of Spanish coal thermal plants, retrofits are limited to auxiliary units reducing NO_x, SO_2 and PM emissions. The Spanish coal capacity is ca. 10.1 GW (REE, 2017). Practically the whole

* Corresponding author.
E-mail address: diego.garcia@imdea.org (D. García-Gusano).

https://doi.org/10.1016/j.enpol.2017.12.038
Received 3 August 2017; Received in revised form 18 December 2017; Accepted 22 December 2017
Available online 04 January 2018
0301-4215/

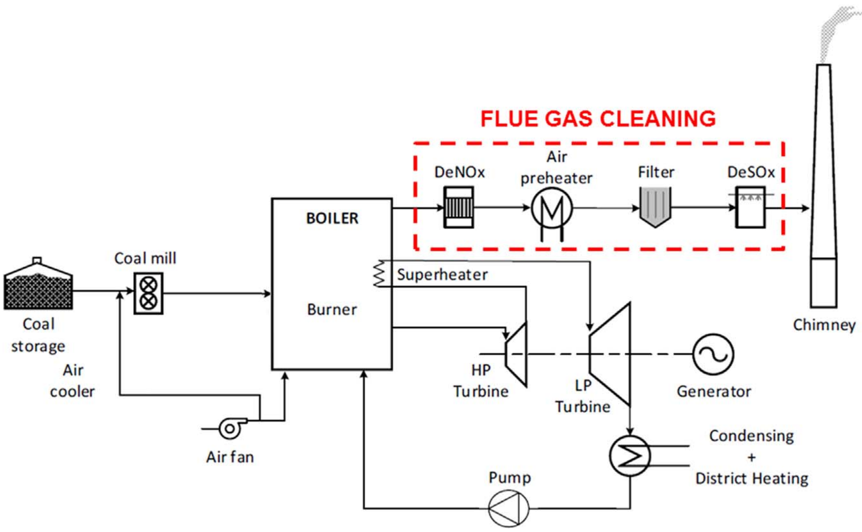

Fig. 1. Scheme of a large coal-fired power plant with flue gas cleaning (modified from Danish Energy Agency (2016)).

sector, except for a 365 MW plant closing by 2023, accepted to be included within the TNP (European Commission, 2016a; MAPAMA, 2015). The Spanish TNP was approved on 25th November 2016 in order to transpose the European IED, assuming the period 2016–2020 as interim to push facilities for investments in less polluting technologies. In particular, the Spanish TNP includes details about the planned measures for each of the power units in every coal-fired plant. Accordingly, there are 5650 MW committed to install deNO_x systems as well as 4070 MW committed to install both deNO_x and deSO_2 systems, in case the corresponding facilities want to continue operating beyond 2020.

Fig. 1 shows the scheme of a coal-fired power plant including flue gas cleaning, i.e. a retrofitted coal power plant. Denitrification systems refer mainly to selective catalytic reduction (SCR) technologies in which NO_x react with ammonia at flue gas temperature (Gutberlet and Schallert, 1993). SCR also decreases secondary fine PM emissions by reducing nitrate aerosol (Li et al., 2015). On the other hand, deSO_x systems comprise a set of flue gas desulphurisation (FGD) methods, being wet or semi-wet scrubbing the most usual one. Since SO_2 is an acid gas, it is necessary to use an alkaline material (e.g., lime) as sorbent. The resulting products are calcium sulphite and water, which can be processed to marketable gypsum (Galos et al., 2003). There are alternative FGD systems using e.g. magnesium hydroxide as sorbent (Córdoba, 2015).

According to the Danish Energy Agency (2016), retrofitting coal-fired power plants could extend the lifetime of these plants up to 15–20 years. Among the list of required works, retrofitting involves replacement of instrumentation and control systems as well as revision of electrical systems. Furthermore, the implementation of flue gas cleaning technologies requires electricity, thereby reducing the net efficiency of the power plant. A shift from 39% to 38% net efficiency is assumed herein (Carlsson et al., 2014; Danish Energy Agency, 2016; OECD/IEA, 2010). Finally, the costs of retrofitting coal power plants can be found in (Conesa López et al., 2017).

1.2. The energy transition paradox

After the 70's oil crises, many countries began to face the problems associated with the use of fossil fuels. In particular, oil dependence arose as the driving force regarding countries' decisions on energy planning. In this sense, it is generally accepted that a new energy transition from fossil fuels to renewable sources began to happen at that time (Scott, 1994). The first energy transition took place from biomass to coal in the XIX century, later from coal to oil, and we are currently experiencing oil retirement (Allen, 2012).

Energy transitions are lengthy processes usually taking decades or even centuries. According to Sovacool (2016), the transition to coal lasted 96–160 years while the transition to oil was shorter, 47–69 years. Besides, energy transitions are non-linear progressions (Sovacool and Geels, 2016), as observed in the well-known German *Energiewende*, where CO_2 emissions have been growing since plan approval in 2011 (Smil, 2016). In this regard, these CO_2 increases, mostly due to emissions from coal-fired power plants, should be understood as a temporary situation in the transition to a highly renewable long-term electricity mix. This paradoxical effect is usually known as "the coal conundrum".

At some point in the future, renewable energy technologies will be predominant in most of the countries. However, nowadays renewable electricity accounts for only 18.3% of the final energy consumption worldwide (IRENA, 2017). Using recent data from IEA (OECD/IEA, 2016), the coal share in global electricity production meant 40.8% in 2014, natural gas 21.6%, oil 4.3%, nuclear 10.6%, hydro 16.4%, and renewables 6.3%. The comparison with 1973 statistics is relevant. Then, coal meant 38.3%, oil 24.8%, natural gas 12.1%, nuclear 3.3%, hydro 20.9%, and renewables 0.6%. In other words, fossil fuels reduced their contribution from 75% to 67%, with a decreasing relevance of oil but a growing participation of natural gas and coal. Within this context, and considering that the coal production peak could happen in the period 2042–2062 (Maggio and Cacciola, 2012), it is necessary to discuss in depth the role played by coal within the fossil-renewable energy transition.

The role of coal is different depending on the country. For instance, most of the European nations have experienced the retirement of coal from their electricity production mix mainly due to the increasing environmental awareness regarding climate change. However, there are exceptions such as Poland, a great coal producer and consumer, whose economy is largely based on this commodity. The case of Spain is pertinent for analysis because it is a country that still uses coal and is on the edge of a "coal conundrum" situation similar to the German energy transition paradox. By 2021, a nuclear phase-out will begin in Spain and the use of coal could play a significant role for a long-term transition to an almost 100% renewable electricity production mix. Consequently, it is necessary to develop and apply a methodological framework able to evaluate prospectively the key sustainability aspects associated with the techno-economic evolution of the national power generation mix under alternative energy scenarios based on the lifetime extension of retrofitted coal-fired power plants.

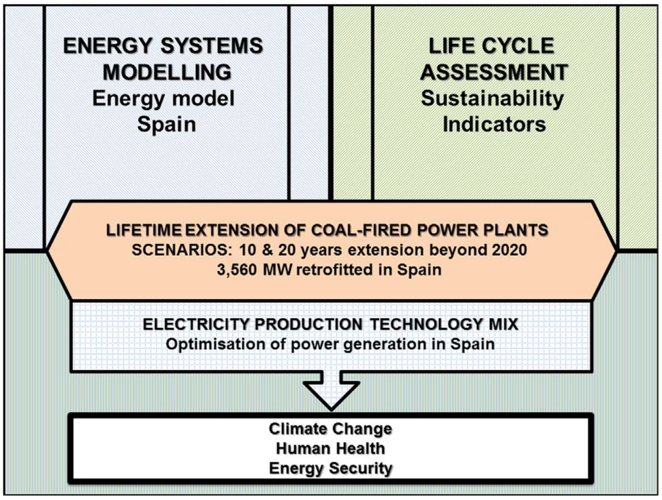

Fig. 2. Methodological framework for the prospective assessment of sustainability indicators integrated in the model of power generation in Spain with scenarios on lifetime extension of coal-fired power plants.

2. Methodological framework

2.1. Combining energy systems modelling and life cycle assessment

Fig. 2 represents the methodological framework for the prospective assessment of power generation in Spain, which is based on the synergistic combination of ESM and Life Cycle Assessment (LCA). On the one hand, ESM enables the creation of energy policies and plans by using powerful mathematical tools. In this article, ESM is focused on optimisation techniques, i.e. giving freedom to the model in order to explore the (economically) optimal combination of technologies and fuels which satisfy the energy system's needs under a set of constraints. Thus, it is possible to explore the evolution of the future electricity production mix in Spain, focusing on the role of retrofitted coal-fired power plants.

ESM alludes to dozens of energy system models with many different approaches depending on the strategy, mathematical procedure, etc. In this study, the Long-range Energy Alternatives Planning System (LEAP) (Heaps, 2016) is used for the creation of scenarios of the Spanish power generation sector. The selection of LEAP is based on its practicality (annual time-step, flexible time horizon, etc.) and flexibility, allowing both backcasting and exploration of scenarios (Connolly et al., 2010). Moreover, the use of OSeMOSYS –a free and open source energy modelling system written in a simple, open, flexible and transparent manner (Howells et al., 2011)– in combination with LEAP allows developing energy scenarios founded on the optimisation of the system's costs. In particular, optimal electricity production mixes of the Spanish energy system are obtained by using the LEAP model already developed for power generation in Spain (García-Gusano et al., 2016). The costs and efficiencies considered for the electricity production technologies are summarised in Table A.1 (Appendix A). Besides, the electricity demand projection is assumed at the sectoral level based on specific econometric functions where gross domestic product, population and electricity prices are the main drivers (Appendix A, Fig. A.1).

On the other hand, LCA is a standardised methodology to evaluate the environmental impacts of a product system across its life cycle, from resource extraction to final disposal (ISO, 2006). Among the most relevant impact categories evaluated in LCA of energy systems, climate change (CC) and human health (HH) are selected in this study since they have already been endogenously integrated into the Spanish LEAP model for their prospective assessment (García-Gusano et al., 2016). Consequently, the evolution of these life-cycle sustainability indicators from present to 2050 is analysed in accordance with the evolution of the future mix of power generation technologies. The software SimaPro 8 (Goedkoop et al., 2016) is used to carry out the LCA of power generation technologies (García-Gusano et al., 2016).

Furthermore, energy security is prospectively evaluated using a life cycle-based indicator. In this respect, taking advantage of the capabilities of the already available Renewable Energy Security Index (RESI) (García-Gusano et al., 2017), it is possible to provide the analysis of power generation in Spain with a prospective approach to energy security. RESI is calculated as the summation of the product of the electricity demand satisfaction (EDS, techno-economic component) and the national renewability factor (NRF, life-cycle component based on cumulative energy demand indicators) for every power generation technology. Thus, RESI has been selected among the dozens of energy security indicators and indices (Ang et al., 2015; APERC, 2007) due to its comprehensiveness and suitability in prospective evaluation as an easy-to-report and practical indicator to use in energy policy (Science for Environment Policy, 2017).

2.2. Description of scenarios

The prospective assessment of the three selected life-cycle indicators (CC, HH, and RESI) facilitates a robust, sustainability-oriented discussion on the suitability of the evolution of the power generation sector according to a set of energy scenario narratives based on techno-economic optimisation. If no extra time is given to the Spanish nuclear power plants (7.7 GW in 6 plants in 2016) beyond their 40-year operating licences, the need to fill the supply gap will grow during the next decade insofar as new renewable facilities cannot deal with the dispatchability levels required in terms of base load. Thus, the very likely nuclear phase-out process to happen in Spain during the period 2021–2028 could lead to a Germany-like "coal conundrum" situation. To face this concern, natural gas combined cycle (NGCC) power plants seem to be the straightforward solution when peak power demand is high, especially during heat or cold waves in seasons of low renewable power generation.

However, coal should not be neglected as a potential solution. If global coal prices –as well as CO_2 prices in the EU Emissions Trading System– are low enough, plant owners could invest in retrofitting coal-fired power plants by implementing denitrification and desulphurisation systems. Under these "favourable" circumstances, and in compliance with the European IED, coal extension in Spain could take place. Hence, in addition to a business-as-usual (BaU) scenario, this article explores two alternative scenarios based on coal extension beyond 2020 (Table 1). This lifetime extension is assumed to affect 3560 MW of the Spanish coal-based power capacity (Fernández Montes, 2016). The selection of 10- and 20-year extension is founded on the techno-economic expectations that retrofitting coal power plants involve (Conesa López et al., 2017). In fact, a recent stress test for coal in Europe suggests a coal shut down schedule in line with this scenario description (Climate Analytics, 2017). Finally, it should be noted that this study does not consider other potentially relevant aspects such as the application of carbon taxes and sensitivity to e.g. variation in energy prices.

3. Results

3.1. Evolution of electricity production

By implementing the energy scenarios described in Table 1 in the Spanish LEAP model, a set of conventional (evolution of electricity production by technology and fuel, capacity installed, direct emissions, etc.) and unconventional (evolution of life-cycle indicators) results coming from the cost optimisation procedure can be obtained. This section focuses on the evolution of the Spanish electricity production by technology under the three scenarios considered (Figs. 3–5).

Under a BaU situation, Fig. 3 shows that coal is retired from the

Table 1
Description of the three scenarios considered for power generation in Spain.

Code	Scenario	Characteristics
BaU	Business-as-Usual	It includes calibrations until 2016 regarding electricity production and capacities. It considers CO_2 emission reduction by 40% with respect to 1990 levels by 2030 at sector level (from then on, direct CO_2 emission is kept constant, meaning annually 39 Mt CO_2).
COAL10	10-year coal extension	It modifies BaU by implementing a 10-year extension for 3560 MW of existing coal thermal power in Spain. It adds $deNO_x$ systems (assumed as SCR) and $deSO_2$ systems (assumed as FGD) for flue gas treatment. Capital costs: 0.16 M€/MW. Fixed O&M costs: 50 €/MW. Variable O&M costs: 5.5 €/MWh. Efficiency reduction: 1%.
COAL20	20-year coal extension	It modifies BaU by implementing a 20-year extension for 3560 MW of existing coal thermal power plants in Spain. It adds $deNO_x$ systems (assumed as SCR) and $deSO_2$ systems (assumed as FGD) for flue gas treatment. Capital costs: 0.16 M€/MW. Fixed O&M costs: 50 €/MW. Variable O&M costs: 5.5 €/MWh. Efficiency reduction: 1%.

production mix in 2020–2023, while nuclear power progressively disappears according to the expiration of the operating licences by 2028. In contrast, existing NGCC power plants will continue in operation until 2037–2040 mainly because most of these facilities were built in 2005–2010. Hydropower remains stationary throughout the entire time frame due to the long life of hydropower plants. Besides the retirement profile of the existing technologies, the growing electricity needs will require new installations. It is noticeable the emergence of new natural gas cogeneration plants in 2016–2020, followed by a large emergence of onshore wind, photovoltaic (PV) and waste-to-energy (incineration) facilities after 2020. Moreover, there is a second renewable rise after 2040 due to the retirement of NGCC power plants and the emergence of offshore wind farms and solar thermal plants with storage (parabolic troughs with 7.5 h storage). It should be noted that NGCC plants with CO_2 capture emerge as of 2025, but playing a minor role. Finally, a slight presence of geothermal power and solid oxide fuel cells (SOFC; fed with natural gas) is observed in the long term.

Figs. 4 and 5 include not only the evolution of the electricity production mix in COAL10 and COAL20 scenarios but also the comparison between COAL and BaU scenarios. This comparison (right-hand side of Figs. 4 and 5) should be understood as the subtraction between the electricity production mix of the corresponding COAL scenario (left-hand side of Figs. 4 and 5) and that of the BaU scenario (Fig. 3). Overall, when comparing BaU and coal extension scenarios, changes in the electricity production profile are found to be relatively small (involving below 12 TWh in every technology).

Regarding the COAL10 scenario, Fig. 4 shows a similar performance to that observed in Fig. 3 for BaU, i.e. the fossil-renewable energy transition continues to take place. It is found that coal extension beyond 2023 leads to a slight contribution of retrofitted coal-fired power plants to the electricity production mix until 2033, with a peak contribution of 8.9 TWh in 2024. Furthermore, the comparison between BaU and COAL10 production mixes shows that coal extension displaces waste-to-energy plants while promoting a higher contribution of NGCC plants

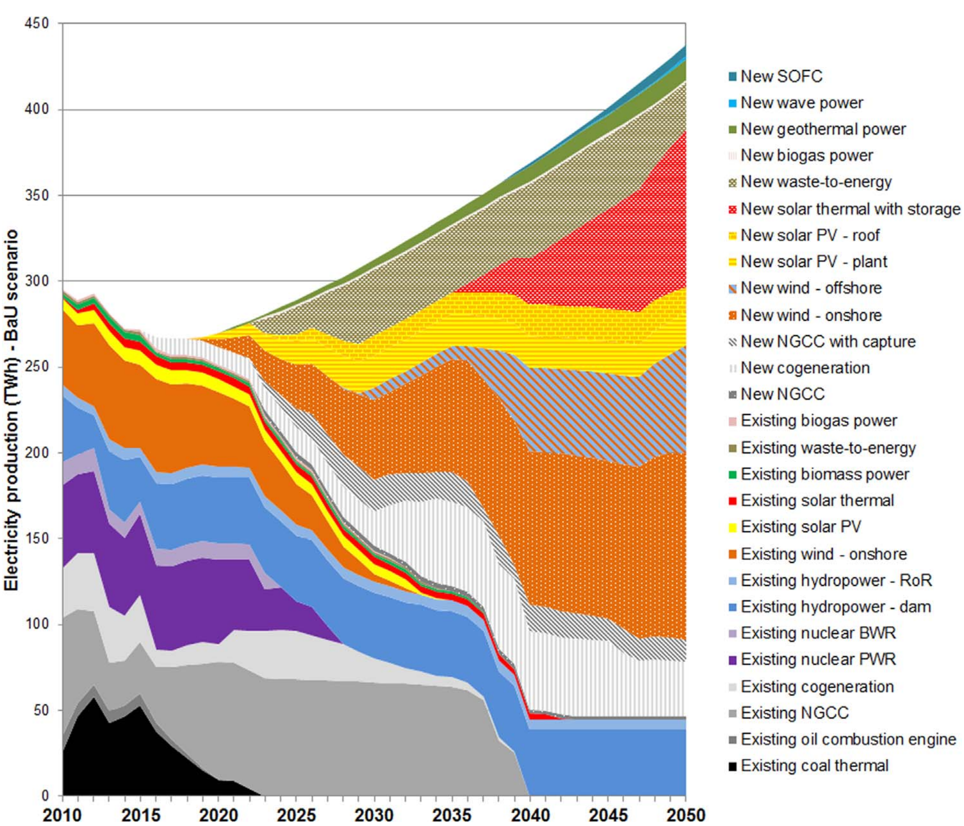

Fig. 3. Evolution of electricity production in Spain: BaU scenario.

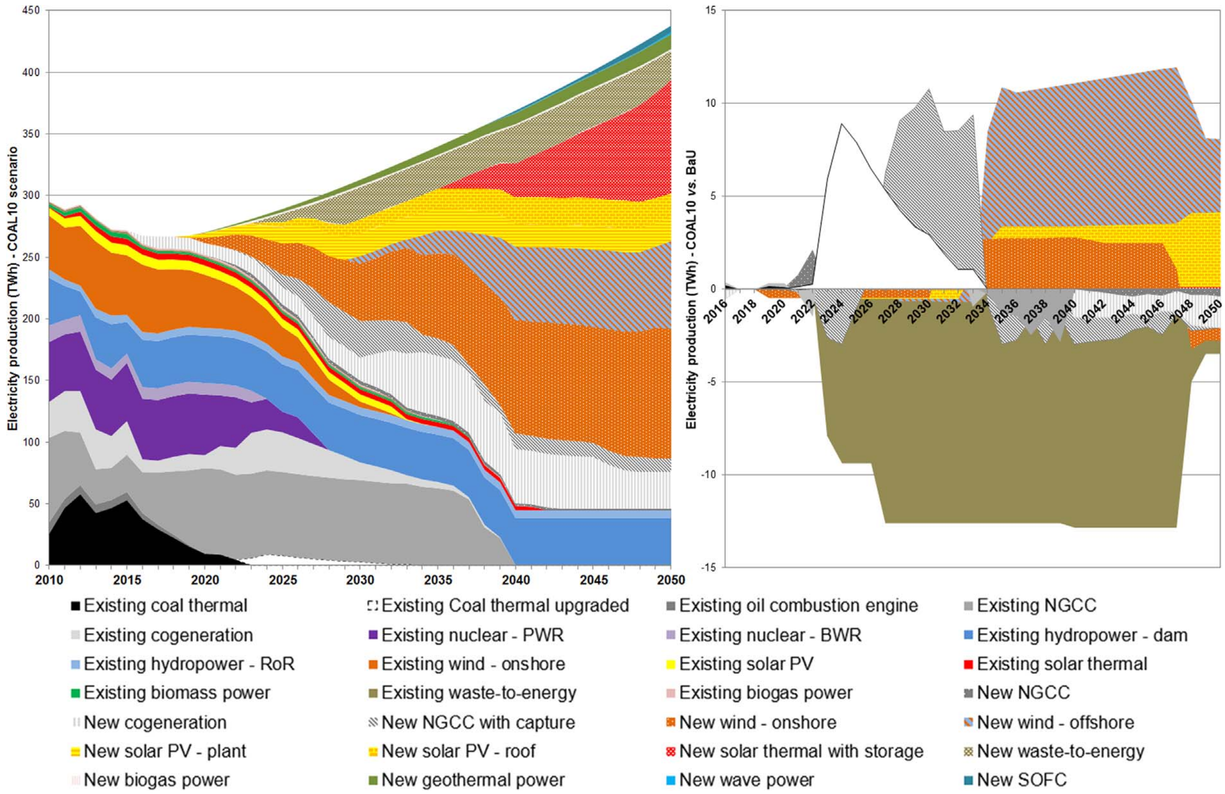

Fig. 4. Evolution of electricity production in Spain under the COAL10 scenario (left) and comparison with BaU (right).

with (post-combustion) CO_2 capture in 2028–2034 as well as of offshore wind farms from 2035 on. To a lesser extent, slightly higher contributions of solar PV and onshore wind facilities are also promoted.

With regard to the COAL20 scenario, Fig. 5 shows how retrofitted coal-fired power plants contribute to the electricity promotion mix until the end of 2043. There are two main contribution peaks: one in 2025 and another in 2038. In this scenario, in comparison with BaU, coal extension leads to diminish the contribution of waste-to-energy plants

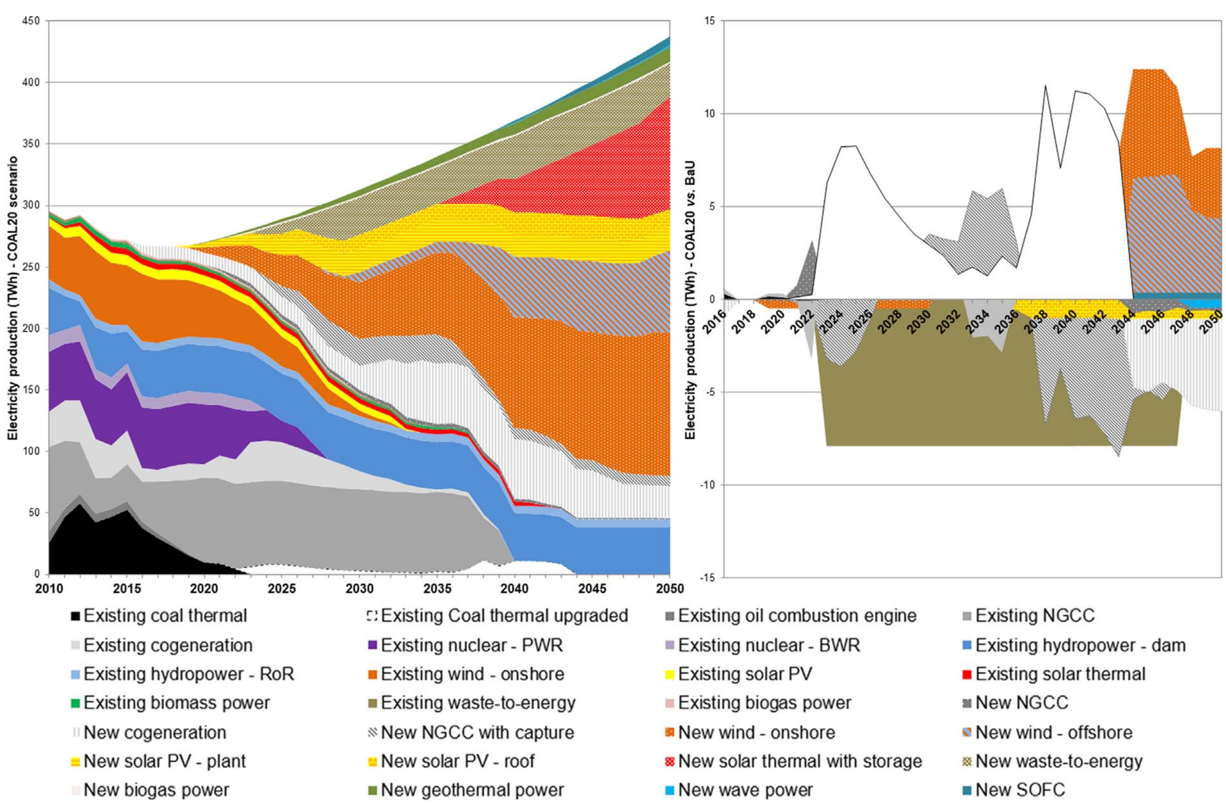

Fig. 5. Evolution of electricity production in Spain under the COAL20 scenario (left) and comparison with BaU (right).

as well as of NGCC plants with CO_2 capture and new cogeneration plants. In contrast, coal extension results in a higher presence of wind technologies, both onshore and offshore, in the long term.

Coal extension causes a double effect on the contribution of renewables to the electricity production mix. By the time that coal plants are retrofitted, a non-investment in new installations takes place. Those non-installed technologies are primarily NGCC with CCS, waste-to-energy, and wind onshore (in comparison with BaU). On the contrary, by the time that existing NGCC plants begin to be retired due to their lifespan (2038–2039), the emergence of new capacity is favoured in order to fulfil a growing electricity demand. This new capacity installation mainly involves new wind offshore farms and solar thermal with storage.

In terms of total system costs, coal extension is found to lead to lower costs than the BaU scenario. In this sense, the COAL20 scenario involves the most affordable option, with −1.37% of the cumulated system costs for the whole modelling horizon with respect to BaU. Similarly, this percentage is −1.04% for the COAL10 scenario in comparison with BaU. This is explained by the fact that retrofits in coal power plants mean less capital intensive investments than new capacity additions.

3.2. Evolution of sustainability indicators

3.2.1. Climate change

Traditional approaches to sustainability in ESM are limited to the evolution of direct emissions coming from energy technologies. However, thanks to the endogenous integration of life-cycle indicators into the LEAP model of power generation in Spain (García-Gusano et al., 2016), this article addresses the evolution of CC, HH and RESI following a holistic approach. Within this context, "endogenous integration" means that the selected life-cycle indicators are an actual component of the energy model, and thus their evolution is a straightforward result from the application of the ESM tool (García-Gusano et al., 2016).

The influence of coal extension on the evolution of climate change is shown in Fig. 6. Overall, a significant reduction in CC is observed for the three scenarios when comparing the values in 2050 with those in 2016. Notwithstanding, there are two main CC concerns associated with coal extension. First, in the period 2022–2034, the two coal extension scenarios involve a significant increase in CC when compared to BaU. For instance, the COAL10 scenario leads to a 19% increase in CC in 2024. Finally, in the period 2040–2044, the COAL20 scenario is found to be significantly detrimental in terms of CC (e.g., 38% increase in 2040 with respect to BaU).

Under the context of the proposed climate change goals by 2030 of the European Union, there is a target of 26% greenhouse gas emission savings in Spain with respect to 2005 levels (European Commission, 2016b). In this sense, coal extension would lead to a breach of duty with regard to the national commitments to face climate change.

3.2.2. Human health

Human health is a complex impact category dealing with carcinogens, non-carcinogens, ionising radiation, ozone layer depletion, and respiratory organics and inorganics (Jolliet et al., 2003). It is measured in disability-adjusted life years (DALY). Fig. 7 shows the evolution of HH for the three scenarios evaluated.

HH evolution is closely linked to the combustion of fossil fuels. This explains the high value found in 2016, given the significant role of coal power in the Spanish electricity production mix then. As coal shutdown begins, a significant decrease in HH is observed in 2017–2022. This decreasing trend is unfavourably reversed under both coal extension scenarios after 2022. When compared to BaU, the COAL10 scenario brings about a significant HH increase in the period 2022–2034 (e.g., double HH impact in 2024). In the COAL20 scenario, this undesirable HH increase with respect to BaU is prolonged until 2044 (e.g., triple HH impact in 2040). Hence, coal extension is found to be detrimental not only in terms of CC (Section 3.2.1) but also in terms of HH. This situation would be even worse if a higher share of the installed coal capacity undertook retrofitting works.

3.2.3. Energy security

Energy security is not usually addressed in prospective studies. Nevertheless, RESI has recently been proposed as a practical energy security indicator focused on renewable power generation technologies for both retrospective and prospective assessment, with RESI targets

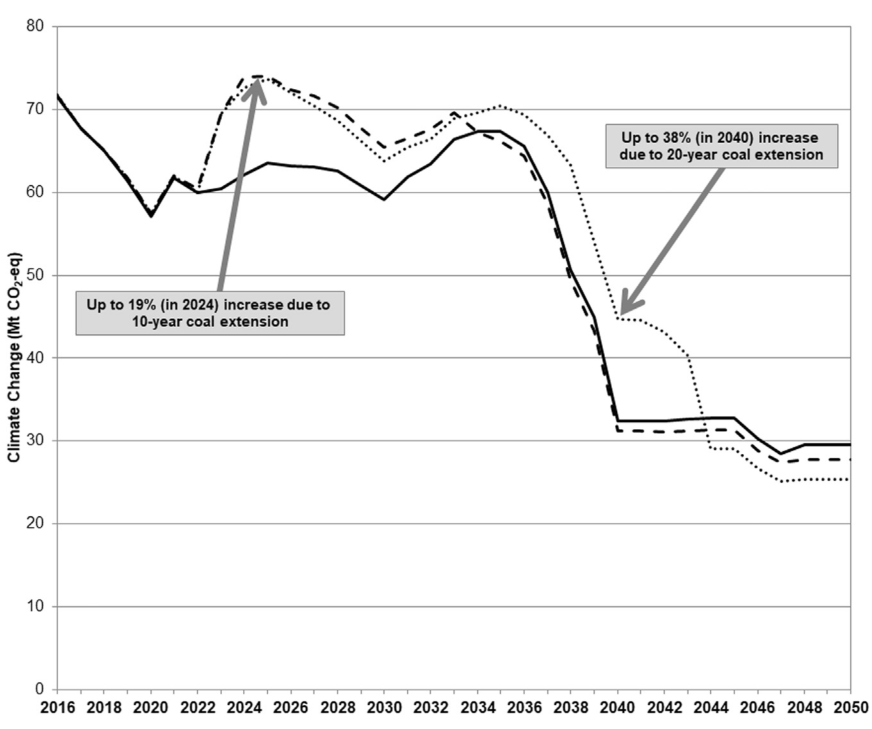

Fig. 6. Evolution of climate change under the three scenarios considered.

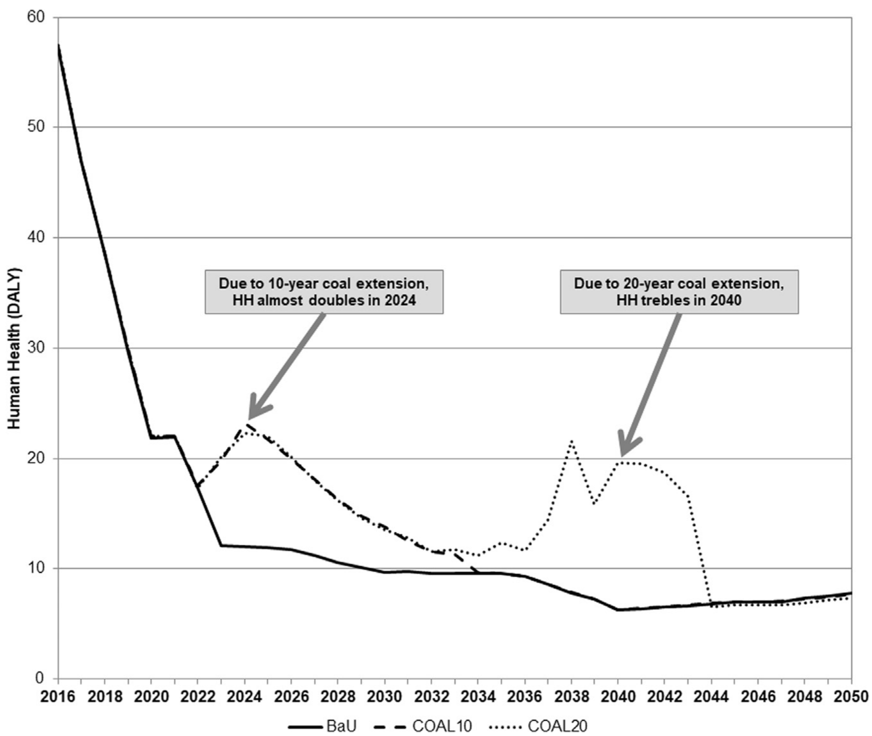

Fig. 7. Evolution of the human health impact under the three scenarios considered.

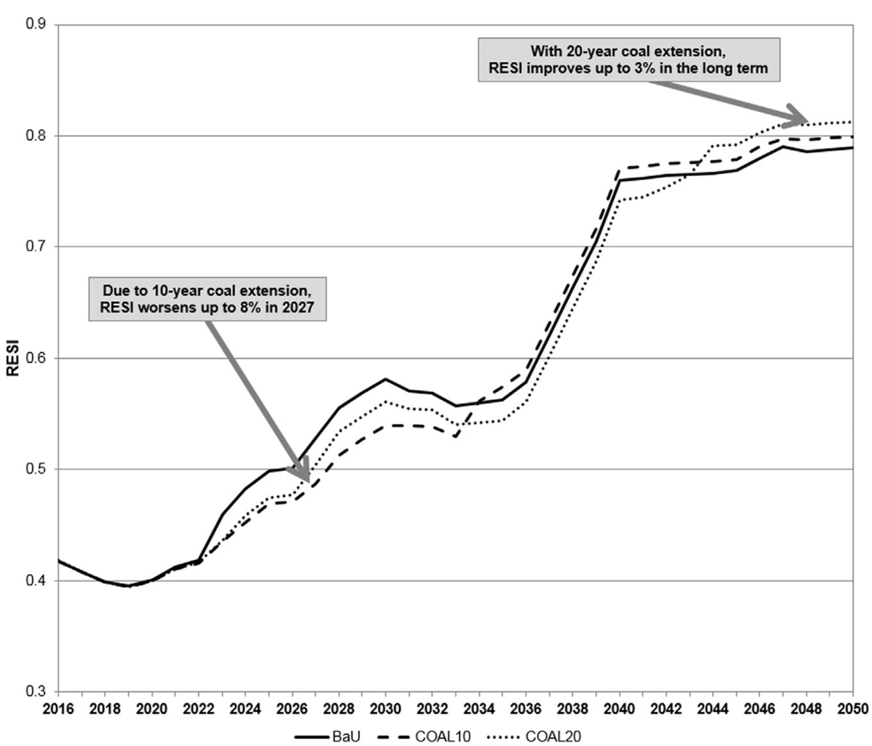

Fig. 8. Energy security evolution under the three scenarios considered.

above 0.8 by 2050 generally considered appropriate (García-Gusano et al., 2017). Fig. 8 shows the evolution of RESI for the three power generation scenarios considered for Spain in this work. Since energy security is a broad concept (Ang et al., 2015), it should be noted that RESI offers a reasonably good –but not total– coverage of key issues around this topic of concern (García-Gusano et al., 2017).

A significant increase in RESI is found in all scenarios, growing from 0.4 in 2016 to around 0.8 in 2050. RESI's growth is driven by the emergence of renewable energy technologies. Consequently, a great increase is observed in the period 2035–2040 due to the retirement of NGCC plants and the subsequent penetration of renewables.

From the comparison of coal extension scenarios and BaU, it is seen that RESI variations are low and behave differently depending on the short- or long-term scope. Regarding the short term (until 2030), coal extension scenarios are detrimental to the energy security profile, involving up to 8% RESI reductions in the COAL10 scenario with respect to BaU. In contrast, in the long term (especially beyond 2043), coal extension scenarios score slightly better than BaU in terms of energy security. For instance, the COAL20 scenario involves a 3% RESI increase in 2050 with respect to BaU. The reason behind the short-term

behaviour is the relevant presence of coal in the mix, thus diminishing the presence of renewable technologies. On the other hand, the better performance of coal extension scenarios in the long term is linked to the lower presence of cogeneration plants based on natural gas.

Overall, extending the lifetime of a number of coal-fired power plants in Spain does not involve either clear energy security benefits or losses. Since there is an unfavourable RESI behaviour in the short term but a favourable one in the long term, it is not possible to conclude that retrofitting coal-fired power plants in Spain is (un)desirable from an energy security perspective. Hence, the facilitation of decision- and policy-making processes on coal extension should rely on the consideration of other comprehensive indicators such as those addressed in the previous sections. This behaviour found for RESI –which does not lead to an absolute conclusion on the suitability of retrofitting coal-fired power plants in Spain– is closely linked to the double effect caused by coal extension on the contribution of renewables to the electricity production mix, as detailed above in Section 3.1.

4. Advances in the discussion of coal extension scenarios

4.1. Alignment with the needs identified in ESM of coal-oriented scenarios

In a recent article about the role played by renewables in a post-Paris world, Cooper (2016) concluded that renewable technologies would displace fossil and nuclear options from the electricity production mix due to the high cost of conventional options in the long term. However, that article considered only coal-fired power plants provided with CO_2 capture, which imposes a severe economic penalty. On the other hand, an interesting debate on coal was opened by Brathwaite et al., (2010, 2011) when stating that a transition from an oil-based to a coal-based system is desirable, though they neglected the environmental concerns associated with the use of coal in power generation. In this sense, Sovacool et al. (2011) concluded that keeping coal in the electricity production mix would increase the risks derived from environmental damages, and CO_2 capture options would not be a good solution due to concerns on energy penalty and CO_2 storage. In this regard, the prospective assessment carried out in the present article involves a wide portfolio of power generation technologies –including retrofitted coal-fired power plants– and takes into account not only techno-economic aspects but also environmental ones (in particular, climate change).

4.2. Definition of indicators for the suitability of coal extension

It is important to evaluate whether a transition through coal is desirable. Fouquet (2016) discussed about historical energy transitions to conclude that the price of energy services is crucial and energy transitions must be understood as cumulative processes, path-dependent, very complex and very different from one region to another. An illustrative case of coal rise in a transition to more renewables is the German *Energiewende*, motivated under a new energy planning paradigm claiming that decisions on energy issues at present have crucial consequences regarding energy security and sustainability in the future (Fischer et al., 2016). Renn and Marshall (2016) investigated the pros and cons behind the *Energiewende* and concluded that the German plan could act as a role model for other countries that consider a phase-out of both nuclear and coal power plants. Furthermore, Niu et al. (2017) discussed health concerns related to coal-fired power plants in China, proposing an electric power substitution plan oriented towards the enhancement of coal-fired power plants. In this sense, the prospective assessment presented herein benefits from the consideration of energy security and human health impact as additional quantitative indicators –besides climate change and techno-economic parameters– to conclude about the actual suitability of coal extension in Spain.

4.3. Sustainability as the actual driver for sensible energy planning

The future of coal is very country-dependent. Nations with significant coal reserves such as Poland, Australia, China and India are somehow reluctant to increase the contribution of renewables to their electricity production mixes (Gurgul and Lach, 2011; Lucas, 2016). For instance, Wierzbowski et al. (2017) recently proposed a long-term (2050) energy plan for Poland where coal is seen as an option with room for improvement. However, in contrast to the present work, IED restrictions in terms of NO_x, SO_2 and PM emissions were not considered. In fact, coal plants could be further affected by future regulations under discussion, e.g. on the internal market of electricity (potential restriction on technologies emitting over 550 g CO_2 per kWh produced) (European Commission, 2016c). From an energy policy-making perspective, the promotion of business decisions to invest in retrofits in coal-fired power plants should take into account sustainability as the key driver for sensible energy planning (García-Gusano et al., 2016). In this sense, the present article uses a comprehensive approach to support decision-making processes on the suitability of extending the lifetime of Spanish coal-fired power plants, going deeper than traditional techno-economic assessment and adding the sustainability dimension prospectively. In the case of Spain, the evolution of CC and HH (Figs. 6 and 7, respectively) in coal extension scenarios advises against the promotion of retrofitted coal-fired power plants by policy-makers.

Finally, it should be acknowledged that the results presented in this article are focused on the big picture of the Spanish power generation sector and the hypothetical extension of coal-fired power plants. Although a detailed region-specific evaluation could be carried out to refine cost assumptions (Sun et al., 2014), it is out of the scope of the study.

5. Conclusions and policy implications

Since a nuclear phase-out is expected to take place in Spain from 2021, coal power plant owners could take advantage of the current context of low coal and CO_2 prices to contribute to filling the nuclear gap. To do so, they have announced investments in retrofits to reduce NO_x and SO_2 emissions in accordance with the mandatory levels. However, based on the prospective assessment presented in this article, coal extension is concluded not to be a sensible option for energy planning in Spain. Even though coal extension scenarios are found to slightly favour renewable penetration in the long term (mainly wind power), they are unfavourably associated with significant increases in both climate change and human health impact. Thus, when sustainability aspects are taken into account in decision- and policy-making processes, the extended use of coal power plants in Spain is not deemed a suitable solution. In this sense, the prospective assessment of sustainability indicators arises as a key requirement for sound energy planning. Hence, policy-makers are highly recommended to consider sustainability aspects in order to avoid a "coal conundrum" situation in Spain in the forthcoming years.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.12.038.

References

Allen, R.C., 2012. Backward into the future: the shift to coal and implications for the next energy transition. Energy Pol. 50, 17–23.
Ang, B.W., Choong, W.L., Ng, T.S., 2015. Energy security: definitions, dimensions and indexes. Renew. Sustain. Energy Rev. 42, 1077–1093.
APERC, 2007. A quest for Energy Security in the 21st century – Resources and constraints. Asia Pacific Energy Research Centre, Tokyo, Japan (Available at). ⟨http://aperc.ieej.or.jp/file/2010/9/26/APERC_2007_A_Quest_for_Energy_Security.pdf⟩.

Brathwaite, J., Horst, S., Iacobucci, J., 2010. Maximizing efficiency in the transition to a coal-based economy. Energy Pol. 38, 6084–6091.
Brathwaite, J., Horst, S., Iacobucci, J., 2011. Response to "From a hard place to a rock: questioning the energy security of a coal-based economy". Energy Pol. 39, 4671–4672.
Carlsson, J., Pérez Fortes, M.M., de Marco, G., Giuntoli, J., Jakubcionis, M., Jäger-Waldau, A., et al., 2014. Energy Technology Reference Indicator (ETRI) projections for 2010-2050. European Commission, Joint Research Centre - Institute for Energy and Transport, Luxembourg, Luxembourg (Available at). 〈https://setis.ec.europa.eu/sites/default/files/reports/ETRI-2014.pdf〉 (Accessed 24 October 2017).
Climate Analytics, 2017. A stress test for coal in Europe under the Paris Agreement. Berlin, Germany. Available at: 〈http://climateanalytics.org/files/eu_coal_stress_test_report_2017.pdf〉 (Accessed 23 October 2017).
Conesa López, P.A., Coma Salvans, E., Bobes Miranda, R.A., Antuña Egocheaga, M., 2017. Denitrification of coal thermal power plants: lessons from Aboño 2 (in Spanish) 50. Cuadernos de Energía, pp. 118–126. (Accessed 24 October 2017). https://www.enerclub.es/file/_pEP2v7fPjbLTugIYxDKfA;jsessionid=185BFC752D36058492047B5B923B973F.
Connolly, D., Lund, H., Mathiesen, B.V., Leahy, M., 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl. Energy 87, 1059–1082.
Cooper, M., 2016. Renewable and distributed resources in a post-Paris low carbon future: the key role and political economy of sustainable electricity. Energy Res. Soc. Sci. 19, 66–93.
Córdoba, P., 2015. Status of Flue Gas Desulphurisation (FGD) systems from coal-fired power plants: overview of the physic-chemical control processes of wet limestone FGDs. Fuel 144, 274–286.
Council of the European Union, 2010. Council decision of 10 December 2010 on state aid to facilitate the closure of uncompetitive coal mines (2010/787/EU). Off. J. Eur. Union. L336, 24–29.
Danish Energy Agency, 2016. Technology data for energy plants. Updated chapters. August 2016. Centre for Climate and Energy Economics. Copenhagen, Denmark. Available at: 〈https://ens.dk/sites/ens.dk/files/Analyser/update_-_technology_data_catalogue_for_energy_plants_-_aug_2016.pdf〉 (Accessed 23 October 2017).
European Commission, 2016a. Commission Decision of 3.3.2016 on the notification by the Kingdom of Spain of a modified transitional national plan referred to in article 32(6) of Directive 2010/75/EU on industrial emissions (only the Spanish text is authentic). Official Journal of the European Journal (2016/C 89/07).
European Commission, 2016b. Factsheet on the Commission's proposal on binding greenhouse gas emission reductions for Member States (2021–2030). Brussels 20 July 2016. Available at: 〈http://europa.eu/rapid/press-release_MEMO-16-2499_en.htm〉 (Accessed 23 October 2017).
European Commission, 2016c. Proposal for a regulation of the European Parliament and of the Council on the internal market for electricity. COM(2016) 861 final – 2016/0379 (COD). Available at: 〈http://eur-lex.europa.eu/legal-content/EN/TXT/?Uri=COM:2016:861:FIN〉 (Accessed 23 October 2017).
European Parliament and European Council, 2010. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast). Official Journal of the European Union. L334, 17–119. Available at: 〈http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?Uri=OJ:L:2010:334:0017:0119:en:PDF〉 (Accessed 23 October 2017).
Fernández Montes, Y., 2016. The Industrial Emissions Directive and Coal Thermal Power Plants in Spain (in Spanish) 47. Cuadernos de Energía, pp. 156–163. 〈http://www.enerclub.es/file/6YNhYsxWIbu3D5nSJSeWkA;jsessionid=0EF08C932F04F9FF51852DD2426CC951〉 (accessed 24 October 2017).
Fischer, W., Hake, J.F., Kuckshinrichs, W., Schröder, T., Venghaus, S., 2016. German energy policy and the way to sustainability: five controversial issues in the debate on the "Energiewende". Energy 115, 1580–1591.
Fouquet, R., 2016. Historical energy transitions: speed, prices and system transformation. Energy Res. Soc. Sci. 22, 7–12.
Galos, K.A., Smakowski, T.S., Szlugaj, J., 2003. Flue-gas desulphurisation products from Polish coal-fired power-plants. Appl. Energy 75, 257–265.
García-Gusano, D., Martín-Gamboa, M., Iribarren, D., Dufour, J., 2016. Prospective analysis of life-cycle indicators through endogenous integration into a national power generation model. Resources 5, 39.
García-Gusano, D., Iribarren, D., Garraín, D., 2017. Prospective analysis of energy security: a practical life-cycle approach focused on renewable power generation and oriented towards policy-makers. Appl. Energy 190, 891–901.
Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2016. Introduction to LCA with SimaPro. PRéConsultants. Amersfoort, The Netherlands.
Gurgul, H., Lach, Ł., 2011. The role of coal consumption in the economic growth of the Polish economy in transition. Energy Pol. 39, 2088–2099.
Gutberlet, H., Schallert, B., 1993. Selective catalytic reduction of NO_x from coal fired power plants. Catal. Today 16, 207–235.
Heaps, C.G., 2016. Long-range Energy Alternatives Planning (LEAP) system. Stockholm Environment Institute, Somerville, USA (Available at). 〈https://www.energycommunity.org〉 (Accessed 23 October 2017).
Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: the Open Source Energy Modeling System: an introduction to its ethos, structure and development. Energy Pol. 39, 5850–5870.
IRENA, 2017. REthinking Energy 2017: Accelerating the Global Energy Transformation. Renewable Energy Agency, Abu Dhabi, United Arab Emirates (accessed 23 October 2017). http://www.irena.org/DocumentDownloads/Publications/IRENA_REthinking_Energy_2017.pdf.
ISO, 2006. ISO 14044:2006. Environmental Management – Life Cycle Assessment – Requirements and guidelines. International Organization for Standardization, Geneva, Switzerland.
Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. IMPACT 2002 +: a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8, 324–330.
Li, Z., Jiang, J., Ma, Z., Wang, S., Duan, L., 2015. Effect of selective catalytic reduction (SCR) on fine particle emission from two coal-fired power plants in China. Atmos. Environ. 120, 227–233.
Lucas, A., 2016. Stranded assets, externalities and carbon risk in the Australian coal industry: the case for contraction in a carbon-constrained world. Energy Res. Soc. Sci. 11, 53–66.
Maggio, G., Cacciola, G., 2012. When will oil, natural gas, and coal peak? Fuel 98, 111–123.
MAPAMA, 2015. Transitional National Plan of Spain – Directive 2010/75/EU Large combustion plants. Spanish Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA), Madrid, Spain (Available at). 〈http://www.mapama.gob.es/es/calidad-y-evaluacion-ambiental/participacion-publica/pnt_grandes_instalaciones_combustion.aspx〉.
OECD/IEA, 2010. Power Generation from Coal – Measuring and Reporting Efficiency Performance and CO_2 emissions. International Energy Agency, Paris, France.
OECD/IEA, 2016. Key World Energy Statistics. International Energy Agency, Paris, France (Available at). 〈https://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf〉.
Niu, D., Song, Z., Xiao, X., 2017. Electric power substitution for coal in China: status quo and SWOT analysis. Renew. Sustain. Energy Rev. 70, 610–622.
REE, 2017. The Spanish electricity system 2016, Red Eléctrica de España (REE). Alcobendas, Spain. Available at: 〈http://www.ree.es/en/statistical-data-of-spanish-electrical-system/annual-report/spanish-electricity-system-2016-report〉 (Accessed 23 October 2017).
Renn, O., Marshall, J.P., 2016. Coal, nuclear and renewable energy policies in Germany: from the 1950s to the "Energiewende". Energy Pol. 99, 224–232.
Science for Environment Policy, 2017. Renewable Energy's Role in national energy security rated by new index. Science for Environment Policy (Issue 491). European Commission DG Environment, Bristol, UK.
Scott, R., 1994. The history of the International Energy Agency 1974–1994 – IEA the First Twenty Years –Vol. 1. Origins and structure. OECD/IEA, Paris, France (Available at). 〈https://www.iea.org/media/about/1ieahistory.pdf〉 (Accessed 23 October 2017).
Smil, V., 2016. Examining energy transitions: a dozen insights based on performance. Energy Res. Soc. Sci. 22, 194–197.
Sovacool, B.K., 2016. How long will it take? Conceptualizing the temporal dynamics of energy transition. Energy Res. Soc. Sci. 13, 202–215.
Sovacool, B.K., Cooper, C., Parenteau, P., 2011. From a hard place to a rock: questioning the energy security of a coal-based economy. Energy Pol. 39, 4664–4670.
Sovacool, B.K., Geels, F.W., 2016. Further reflections on the temporality of energy transitions: a response to critics. Energy Res. Soc. Sci. 22, 232–237.
Sun, J., Schreifels, J., Wang, J., Fu, J.S., Wang, S., 2014. Cost estimate of multi-pollutant abatement from the power sector in the Yangtze River Delta region of China. Energy Pol. 69, 478–488.
Wierzbowski, M., Filipiak, I., Lyzwa, W., 2017. Polish energy policy 2050 – An instrument to develop a diversified and sustainable electricity generation mix in coal-based energy system. Renew. Sustain. Energy Rev. 74, 51–70.